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Review

Transitional states in marine fisheries: adapting to predicted global change

M. Aaron MacNeil[1,*], Nicholas A. J. Graham[2], Joshua E. Cinner[2], Nicholas K. Dulvy[3], Philip A. Loring[4], Simon Jennings[5,6], Nicholas V. C. Polunin[7], Aaron T. Fisk[8] and Tim R. McClanahan[9]

[1]*Australian Institute of Marine Science, PMB 3 Townsville MC, Townsville, Queensland 4810, Australia*
[2]*ARC Centre of Excellence for Coral Reef Studies, James Cook University, Townsville, Queensland 4810, Australia*
[3]*Earth to Ocean Research Group, Biological Sciences, Simon Fraser University, Burnaby, BC, Canada V5A 1S6*
[4]*Alaska Center for Climate Assessment and Policy, University of Alaska Fairbanks, Fairbanks, AK, USA*
[5]*Centre for Environment, Fisheries and Aquaculture Science, Lowestoft Laboratory, Lowestoft, Suffolk NR33 0HT, UK*
[6]*School of Environmental Sciences, University of East Anglia, Norwich, Norfolk NR4 7TJ, UK*
[7]*School of Marine Science and Technology, Newcastle University, Newcastle upon Tyne NE1 7RU, UK*
[8]*Great Lakes Institute for Ecological Research, University of Windsor, Windsor, ON, Canada N9B 3P4*
[9]*Wildlife Conservation Society, Marine Programs, Bronx, NY 10460, USA*

Global climate change has the potential to substantially alter the production and community structure of marine fisheries and modify the ongoing impacts of fishing. Fish community composition is already changing in some tropical, temperate and polar ecosystems, where local combinations of warming trends and higher environmental variation anticipate the changes likely to occur more widely over coming decades. Using case studies from the Western Indian Ocean, the North Sea and the Bering Sea, we contextualize the direct and indirect effects of climate change on production and biodiversity and, in turn, on the social and economic aspects of marine fisheries. Climate warming is expected to lead to (i) yield and species losses in tropical reef fisheries, driven primarily by habitat loss; (ii) community turnover in temperate fisheries, owing to the arrival and increasing dominance of warm-water species as well as the reduced dominance and departure of cold-water species; and (iii) increased diversity and yield in Arctic fisheries, arising from invasions of southern species and increased primary production resulting from ice-free summer conditions. How societies deal with such changes will depend largely on their capacity to adapt—to plan and implement effective responses to change—a process heavily influenced by social, economic, political and cultural conditions.

Keywords: climate change; fish communities; social–ecological systems; biodiversity

1. INTRODUCTION

Achieving sustainable fisheries is among the most challenging large-scale management problems globally. Just as evidence for reductions in exploitation rates is emerging in some wealthier regions (Beddington *et al.* 2007; Worm *et al.* 2009), concerns are growing about the fisheries implications of global climate warming. Although climate-driven change is expected in every marine ecosystem, the science needed for regional-scale ecological understanding is immature and thus the magnitude and extent of effects remain largely unknown. Yet adaptation of fisheries and fisheries management to a changing environment is necessary when nearly 1.5 billion people rely on fish for more than 20 per cent of their protein (Badjeck *et al.* 2010) and global fisheries contribute $91.2 billion USD to global agricultural trade (2006 data; FAO 2008).

To date, warming within the world's oceans has been variable in magnitude though unequivocal in scope; all but two of the world's 64 large marine ecosystems (LMEs) experienced warming between 1982 and 2006 (Sherman *et al.* 2009), with the largest increases among shallow shelf and inland sea areas in the North Atlantic. Warming trends are expected to have widespread effects on catch diversity as the distribution of populations changes to reflect the spatial

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[*] Author for correspondence (a.macneil@aims.gov.au; macneil@glau.ca).

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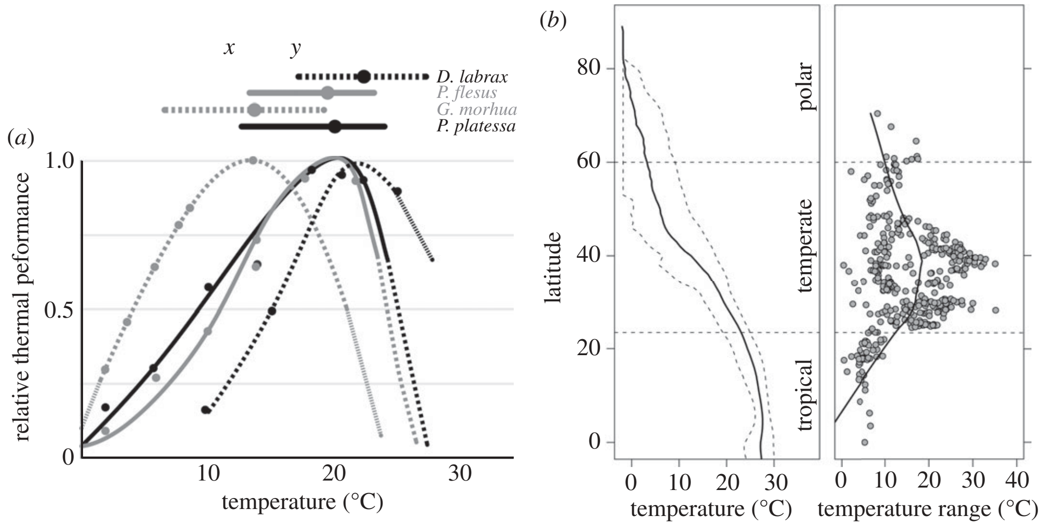

Figure 1. (*a*) Laboratory-based thermal performance profiles for North Sea demersal fishes *Pleuronectes platessa* (black solid line), *Pleuronectes flesus* (grey solid line), *Gadus morhua* (grey dotted line) and *Dicentrarchus labrax* (black dotted line). Relative performance profiles include temperature performance breadths (>69% performance; top horizontal lines) and varying tolerance ranges (solid/dotted curves). Communities assembled at temperature *x* will have a different composition from communities at temperature *y* because of diversity in thermal performance, although performance breadth is likely to be narrower *in situ*. Data from Freitas *et al.* (2007). (*b*) Average Northern Hemisphere sea-surface temperatures (solid line, left panel) with 95% quantile range (of 365 days per 1° latitude–longitude grid cell; dashed lines, left panel) from the 2009 HadISST1 dataset (Rayner *et al.* 2003) alongside seasonal temperature ranges (max–min; grey circles, right panel) from National Oceanic and Atmospheric Administration buoy data (http://www.ndbc.noaa.gov), both by latitude. Buoy data includes a local average line (solid line, right panel) based on the default Loess.smooth function in R.

movement of thermal optima (figure 1*a*; Planque & Frédou 1999; Pörtner 2010). These changes are in addition to well-documented climate variability effects on fisheries from changes in temperature, winds and hydrological cycles (Brander 2010). Warming will probably alter the location of critical fish habitat (Brander 2010); competition and predation dynamics (Graham & Harrod 2009); ecosystem functional roles (Munday *et al.* 2008); food availability (Chase & Liebold 2002); and reproductive success (Edwards & Richardson 2004; Overland *et al.* 2010). Finally, warming trends will also alter ocean chemistry, with potentially negative effects such as ocean acidification and hypoxia (Pörtner 2010) that, given their limited effects to date, we do not consider here.

Beyond the direct effects of increasing temperature, warming also adds energy to the ocean-climate system, increasing the severity of acute disturbance events and generating higher environmental variability. As a result, both the frequency of regional climate anomalies (e.g. El Niño) and the magnitude of physical disturbance events (e.g. storms, coral bleaching) are expected to increase (Timmermann *et al.* 1999). More extreme seasonal shifts may lead to a match–mismatch between larval fish populations and their zooplankton prey (Stenseth *et al.* 2002), as well as unpredictable levels of seasonal upwelling and more variable recruitment (Usher *et al.* 2005; Brander 2009). Although warming trends and acute disturbances are expected to increase across many ecosystems, impacts will be system-dependent (table 1). Polar and tropical ecosystems will probably be more susceptible than temperate systems to climate change because of their low levels of seasonal temperature variation and their proximity to thermal extremes (figure 1*b*).

(a) *Adapting to change*

It is critical for human societies to understand how to adapt to changes in fisheries resources. The impacts on society will depend on their vulnerability, with outcomes heavily influenced by environmental, social, economic, political and cultural considerations. Vulnerability can be conceptualized as having three key components: exposure, sensitivity and adaptive capacity (figure 2; Adger 2006). Exposure is the degree to which a system is stressed, combining the level of human presence in climate-affected areas with the magnitude, frequency and duration of a climatic disturbance event (Cutter 1996; Adger 2006). Sensitivity is the level of susceptibility to harm from climate change and is affected by the level of resource-dependence (Adger 2006; Cinner *et al.* 2009*d*). Adaptive capacity helps to offset impacts and includes preconditions that enable adaptation such as flexibility, learning, social organization and assets, all of which are necessary for successful adaptation (Nelson *et al.* 2007; Cinner *et al.* 2009*b*). Both adaptation and adaptive capacity occur at multiple scales and successful adaptation often requires linkages across scales (Adger *et al.* 2005; Ford *et al.* 2007). These components define our framework for understanding the social impact of climate change in marine fisheries.

Here we consider potential effects of climate change on the biodiversity and productivity of the world's marine fisheries. We employ three case studies to illustrate the kinds of ecosystem change expected in tropical, temperate and polar (Arctic) LMEs, discussing how societies can adapt and outlining key social aspects of vulnerability. Although many negative effects are predicted there may also be benefits (Brander 2010), with ecological and economic winners and losers (Arnason 2007; Cheung *et al.* 2010).

Table 1. Major climate change phenomena currently impacting the diversity of marine fisheries. Primary drivers refer to increased warming through time (trend) and more extreme seasonality and high-energy disturbance events (variation).

phenomenon	process	primary driver	effect on catch diversity (mechanism)	projected ecosystems affected[a]	observed example(s)
range shifts	movement of thermal optima in depth and space	trend	increase or decrease in species richness due to immigration and emigration modified by changing predation and competition	all, but leading to decreased richness at low latitudes and increased richness at high latitudes	North Sea (Perry *et al.* 2005; Dulvy *et al.* 2008; Hiddink & ter Hofstede 2008)
declining production	increased thermal stratification	trend	decrease in species richness owing to lower environmental heterogeneity, lower temporal variation or fewer potential stable states[b]	all (except upwelling areas), fisheries losses may be most severe in temperate areas	tropical latitudes (Behrenfeld *et al.* 2006)
growth rates	increase or decline in thermal performance	trend	increase or decrease in species richness due to change in niche structure	increase in high latitude systems and decrease in low latitude systems	North Atlantic (Dutil & Brander 2003)
habitat loss	physical destruction of critical habitat from storms and coral bleaching	variation	decrease in species richness due to reduced habitat heterogeneity	coral reefs; mangroves; intertidal zones; kelp forests, ice areas	Western Indian Ocean (Graham *et al.* 2008)
declining recruitment	decoupling in the timing of spawning and nutrients; chemical cue failures	variation	decrease in species richness due to decreased larval survivorship	coral reefs; ice areas; shelf areas; pelagic zones	North Atlantic (Planque & Frédou 1999); Great Barrier Reef (Munday *et al.* 2010)

[a] Excluding ecosystems below 200 m which are less fished than other areas.
[b] From Chase & Liebold (2002).

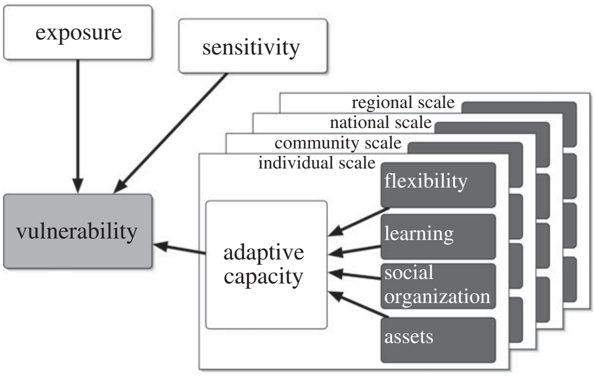

Figure 2. Conceptual framework for understanding components of social vulnerability to climate change. Exposure, sensitivity and the four components of adaptive capacity operate at local, community, national and regional scales to varying degrees, depending on conditions. Adaptive capacity includes aspects of governance, education, health and wealth as aspects of the four components. Based on Cinner *et al.* (2009*b*).

2. TROPICAL FISHERIES: THE WESTERN INDIAN OCEAN

The greatest fisheries losses from climate change are likely to occur among reef-based fisheries. Because reef-building corals exist in low-variation tropical conditions near their upper thermal tolerances (figure 1*b*; Hughes *et al.* 2003; Tewksbury *et al.* 2008), they are susceptible to acute thermal stress that causes them to expel symbiotic zooxanthellae (coral bleaching) and, eventually, die (Hoegh-Guldberg *et al.* 2007). Hard corals are critical for many reef fishes, providing habitat for settlement, physical protection and food (MacNeil *et al.* 2009), while reef fish help corals dominate macroalgae through numerous functional roles (e.g. Wilson 2004; Ledlie *et al.* 2007; Bonaldo & Bellwood 2009). Predicted increases in the magnitude and frequency of acute disturbance events (McClanahan 2002) will probably be responsible for the main climate impacts on tropical fisheries over coming decades, as they destroy reef structure and degrade function (Munday *et al.* 2008).

The potential effects of reef degradation on human societies are substantial. Many societies depend on reef-based fisheries for food and livelihoods and are therefore especially vulnerable (McClanahan *et al.* 2009). Tropical fishers make up more than 90 per cent of the estimated 3.5 million fishermen in the world (Badjeck *et al.* 2010), often in countries twice as dependent on fisheries for dietary protein than other regions (Allison *et al.* 2009). Although the widespread overexploitation in many reef fisheries (Newton *et al.* 2007) may have resulted in communities tolerant to additional climate-change effects (Vinebrooke *et al.* 2004), such effects are not ubiquitous and many reef fisheries remain vulnerable.

Analysis of previous large-scale climatic events may help to anticipate climate effects in tropical fisheries of the future. In 1998, reefs throughout the Western

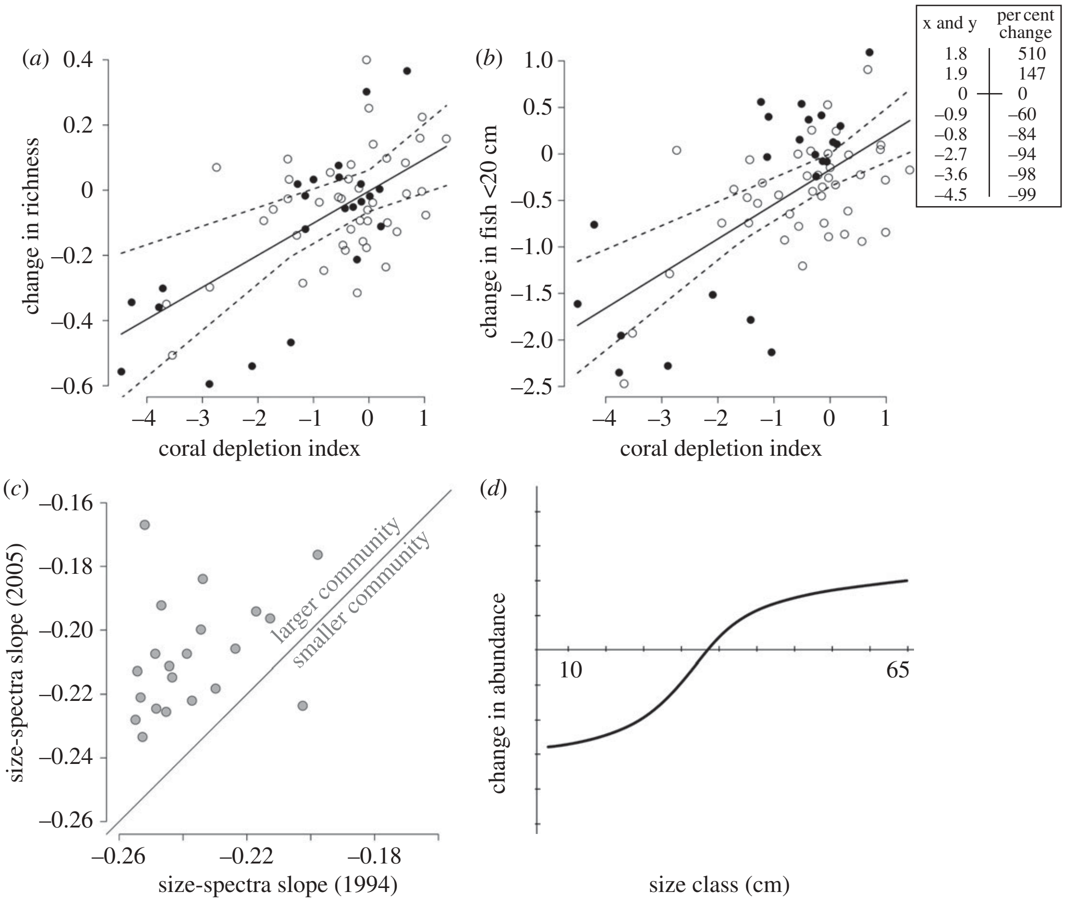

Figure 3. Selected effects of 1998 bleaching event on reef fish community structure in the Western Indian Ocean (WIO) calculated from before (1993–1995) versus after (2005) the 1998 El Niño Southern Oscillation. Observed effects include a lower (*a*) species richness and (*b*) fewer small ($<$20 cm TL) fish, where corals were depleted between the two time periods; open circles indicate fished areas, closed circles have protected status; both axes are scaled relative change indices at 66 locations in eight countries; results include mean trends (solid lines) with Bayesian 95% credible intervals (dashed lines); methods provided in Graham *et al.* (2008). (*c*) Observed decrease in size-spectral slopes at the majority of WIO locations in 2005. Conceptually, these observations reflect (*d*) the growth of the existing fish assemblage from 1994 (abscissa) to 2005 (curved line) coupled with substantial losses of small fish owing to lack of coral cover affecting protection and recruitment (data from Graham *et al.* 2007).

Indian Ocean (WIO) experienced the most severe bleaching event on record, owing to an El Niño Southern Oscillation phase that co-occurred with the Indian Ocean Dipole (Saji *et al.* 1999). The size and scope of the event, combined with widespread ecological monitoring across the WIO, provide a unique, large-scale example of acute disturbance effects in tropical fisheries.

Bleaching occurred across many WIO reefs during 1998, with coral mortality from 1 to 95 per cent depending on local conditions (Graham *et al.* 2008; McClanahan *et al.* 2008). Fish-community effects were apparent throughout the WIO but were patchily distributed, reflecting the dependencies of individual species on corals. In the most severely impacted locations of the northern Indian Ocean, fish diversity declined by 50 per cent, with corallivorous and planktivorous fishes dependent on corals for food and shelter declining by at least 76 and 68 per cent, where coral cover declined by more than 50 per cent (figure 3*a*,*b*; Graham *et al.* 2008; MacNeil & Graham 2010).

As newly recruited coral reef fishes rely heavily on the complexity of coral reefs to provide shelter from predation (Pratchett *et al.* 2008), small fishes were particularly affected by the 1998 bleaching event. The severity of losses among small- and medium-sized fishes was clear from pre- and post-bleaching community size spectra (figure 3*c*), with higher post-bleaching size-spectral slopes reflecting widespread losses of small fish, even when large herbivorous fishes increased in abundance (figure 3*d*; Graham *et al.* 2007). These losses were substantial, affecting both small species and small size classes of larger fishery target species (Graham *et al.* 2007). Because reef fish can be exceptionally long-lived (Choat & Robertson 2002), considerable time lags are expected between the loss of live coral, collapse of the reef structure and declines in remnant fish biomass (Graham *et al.* 2007; Paddack *et al.* 2009). We hypothesize that a positive feedback between losses of coral and losses of fish will generate a higher risk of species extinction among reef-fish communities than elsewhere.

Surprisingly, there appeared to be little immediate impact of the 1998 bleaching event on fish biomass (Grandcourt & Cesar 2003). However, many studies were conducted only several years post-bleaching, with potentially little time for impacts to affect community dynamics. Long-term studies (7–10+ years) are detecting declines in fishery catch consistent with lagged impacts of benthic disturbance in reef fisheries (Pistorius & Taylor 2009). Importantly, many fishers shifted to seagrass-associated species prior to 1998 owing to heavy exploitation (McClanahan *et al.* 2008), thereby buffering local catches from the event. Such resource-shifts may prove critical in areas affected by increased disturbance and overexploitation, although often as less-desirable fisheries with fewer species and lower prices (McClanahan in press).

The capacity of WIO societies to respond to sustained reef fishery losses is heterogeneous; while some groups have strengths in aspects of adaptive capacity, they frequently lack others. Social and governance systems tend to have a reasonable degree of flexibility, such as diverse livelihoods among economic sectors (Cinner & Bodin 2010) and diversity between and within occupations (e.g. the use of several fishing gears) that allow people to switch among economic activities and targets (Turner *et al.* 2007). Parts of the WIO have developed flexible and decentralized management systems that permit rapid implementation of locally appropriate management rules (Cinner *et al.* 2009*c*), however rigid taboos and social norms may constrain adaptation options (Cinner *et al.* 2009*b*).

At both national and local scales, many WIO countries lack assets to effectively navigate planned or autonomous adaptations. In Kenya for instance, where low capital is combined with few livelihood options, fishers readily fall into poverty traps, whereby the absence of credit or savings makes continuing to fish the only option (Cinner *et al.* 2009*d*). At the national scale, high levels of corruption and political conflict can hamper organization and delivery of services during periods of disturbance and climate stress (Barnett & Adger 2007). Although the coral reefs in the WIO region are well studied, feedback about the condition of corals and fisheries is seldom provided to community managers and low levels of education may limit the capacity to synthesize scientific and local knowledge. In sum, many WIO fisheries are likely to be highly vulnerable to climate change owing to significant asset gaps.

3. TEMPERATE FISHERIES: THE NORTH SEA

Temperate fisheries typically experience higher levels of seasonal variation than those in the tropics (figure 1*b*), with species distributed close to the centre of their thermal tolerance range. These factors will typically reduce warming susceptibility, giving temperate fishes greater capacity for range changes. Temperate changes in species composition will thus be driven primarily by poleward movement of boreal fishes out of mid-latitudes and the arrival of warm-water species from lower latitudes. Rapid climate-driven community turnover (i.e. decades; Perry *et al.* 2005) has already been reported from temperate North Atlantic LMEs, currently among the fastest warming in the marine environment (Sherman *et al.* 2009).

The North Sea provides a well-studied example of warming-driven biodiversity change in temperate fisheries, being a shallow basin (<40 m in many places) that has heated up more rapidly than waters at similar latitude. Between 1982 and 2006, North Sea temperatures rose by 1.31°C (Sherman *et al.* 2009), including a dramatic 0.9°C increase in 1989 (Dulvy *et al.* 2008) that led to major biogeographical shifts in community structure. From 1977 to 2001, almost two-thirds of fished species in the North Sea changed their spatial distribution in response to warming (e.g. figure 4*b*,*d*), driven primarily by northward shifts in faster growing species exploiting warmer northerly waters (Perry *et al.* 2005; Hiddink & ter Hofstede 2008). Because the northward emigration of larger, cold-water species progressed more gradually (Perry *et al.* 2005), diversity increased within the North Sea (figure 4*e*,*f*). Southward movements of warm-water species such as sole *Solea solea* and scaldfish *Arnoglossus laterna* into the shallow southern North Sea have also occurred owing to earlier springtime warming (Dulvy *et al.* 2008).

Despite such spatial changes, the most consistent response of North Sea fishes to warming has been a deepening of the assemblage. On average, the assemblage has deepened by 3.6 m decade^{-1}, belying exceptional changes in species such as cod *Gadus morhua* (figure 4*c*) and anglerfish *Lophius piscatorius* (figure 4*a*; Dulvy *et al.* 2008). A widespread change in depth is a predictably efficient response for species as tracking the movement of their thermal optima requires smaller movements with depth or elevation than for latitude (Colwell *et al.* 2008). It is important to note however that the distribution of fishing mortality throughout the North Sea may play a role in these patterns that is difficult to assess.

Movement of thermal optima are not the only process determining fish diversity in the North Sea, as thermally driven shifts in prey base may also be an important factor. Between 1960–1981 and 1988–2001, a 10°C thermal boundary linked to differences in copepod community structure in northwest Atlantic waters moved from the edge of the English Channel into the central basin as community structure changed (Beaugrand *et al.* 2008). While a change in prey base could influence competition among predatory fishes, primary production ultimately drives fisheries production, and changes in total North Sea production are expected to broadly track changes in primary production as in other systems (Chassot *et al.* 2010; Jennings & Brander 2010). Thus, if warming increases thermal stratification and reduces primary production (Behrenfeld *et al.* 2006) there may be a decline in North Sea fisheries yield.

As some of the least fisheries-dependent nations in the world, North Sea fishing nations are among those least vulnerable to climate impacts (Allison *et al.* 2009). Fleets are technologically advanced, being able to change target species through spatial movement and gear changes (Catchpole *et al.* 2005) and fishers have demonstrated capacity to maintain high catch per unit effort even as stocks decline (Hentrich & Salomon 2006; Villasante 2010). This is partly because of European Common Fisheries

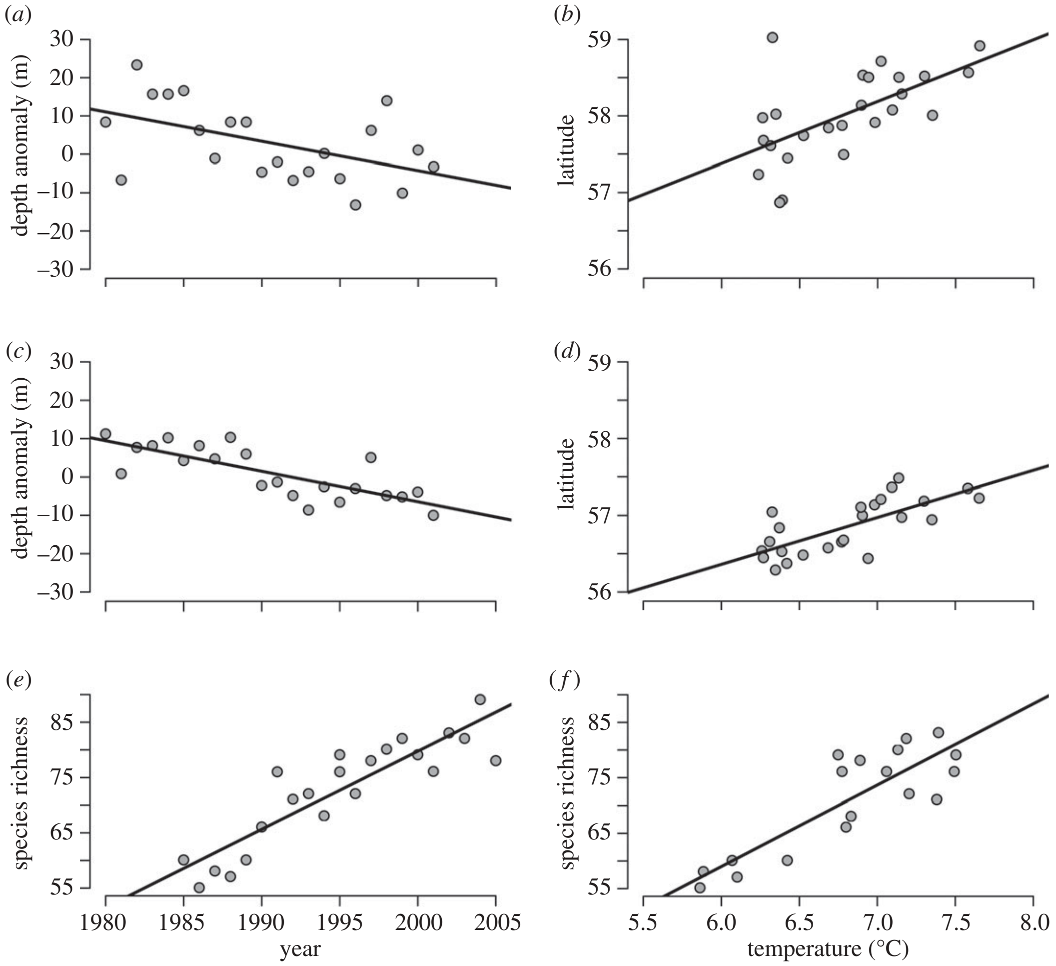

Figure 4. Climate-induced changes in North Sea community structure. Change in anglerfish *Lophius piscatorius* showing (*a*) greater depth distribution through time and (*b*) higher mean latitude with 5-year mean winter bottom temperature; change in cod *Gadus morhua* showing (*c*) greater depth distribution through time and (*d*) higher mean latitude with 5-year mean winter bottom temperature (data from Dulvy *et al.* 2008; Perry *et al.* 2005). Increases in North Sea species richness (*e*) through time and (*f*) with 5-year mean temperatures (data from Hiddink & ter Hofstede 2008). All lines are normal linear regressions run in R, presented to illustrate general trends.

Policy (CFP) historically supporting overcapacity in the region, allowing both sub-optimal fishing and marginal profitability to develop in overexploited stocks (Hentrich & Salomon 2006). Although numbers of boats and fishers have declined in recent years (Villasante 2010), European negotiators have also brokered access to West African or Indo-Pacific fisheries that have buoyed EU fishing capacity.

Fishers in the North Sea are well poised in terms of adaptive capacity to adjust targets to match projected changes in catch. Fisheries have already developed for red mullet *Mullus barbatus*, whose distribution has rapidly expanded into the North Sea during the past 20 years (Beare *et al.* 2004). Households within the EU also have higher than average levels of social and economic flexibility that, albeit often reluctantly, allowed many to leave fishing as catches have declined (Stead 2005). Furthermore, Northern Europe has among the highest levels of scientific and financial assets in the world, with hundreds of fisheries scientists working to understand the effects of climate variability on North Sea stocks. A strong asset and learning base combined with the social flexibility to switch fisheries has allowed some North Sea fishing societies to persist through periods of low catches and reduced quotas.

The greatest gaps in adaptive capacity for North Sea fisheries are therefore regulatory, primarily owing to the inflexibility of EU CFP regulations in responding to changing fishing opportunities (Hentrich & Salomon 2006). To sustainably target fisheries developing as a result of climate, both the industry and management system will need to be made more flexible (Perry *et al.* 2010). In the North Sea context, this requires a management system that is better able to assess and support new sustainable fishing opportunities, rather than being locked in to assessing quotas for a series of populations that provide a falling share of total catch. Changes in population distribution could also lead to challenging negotiations with non-EU countries in the area (e.g. Norway and Iceland), if they assert rights to stocks migrating further out of EU waters. For species of potential commercial value appearing in North Sea waters, simple approaches based on life-history characteristics could be used to provide a first assessment of potential productivity (Beddington & Kirkwood 2005) and in determining whether fishery development could be supported. Such an approach would reduce transitional barriers for fishers exploiting newly arrived species (McIlgorm *et al.* 2010) and may reduce conflicts over jurisdiction and fishing opportunities likely to arise from shifting stocks (Vilhjálmsson *et al.* 2005).

4. ARCTIC FISHERIES: THE BERING SEA

Of the world's 66 LMEs, the Arctic Ocean ecosystem is changing most rapidly owing to systematic losses of multi-year sea ice that defines the environment (Sherman *et al.* 2009). Marginal sea ice—the transitional seasonal ice linking multi-year sea ice and open water—is currently the primary source of production for the Arctic benthic food web, with intense algal growth in spring and summer generating high levels of spatially concentrated primary production (Usher *et al.* 2005). Declines in total sea ice across the Arctic are well-documented (NSIDC 2008) and forecasts suggest that warming may soon generate ice-free summers (Overpeck *et al.* 2005). Arctic marine organisms are particularly susceptible to these effects because they are adapted to life in a low variation environment at the low end of ocean temperatures (figure 1*b*), conditions that will cease to exist in an ice-free Arctic.

The loss of multi-year ice cover will profoundly affect Arctic ecology and will probably lead to positive fisheries effects. While some primary and secondary production will be lost from a potential match–mismatch along marginal sea ice, Arctic primary production is severely light limited by multi-year sea ice. New open-water areas will probably experience an explosion of primary productivity, leading to increased zooplankton abundance and higher fish biomass throughout the region (Loeng *et al.* 2005; Behrenfeld *et al.* 2006; Sherman *et al.* 2009).

The kinds of positive effects of warming expected in the Arctic have already been demonstrated on Arcto-Norweigian cod distributions and abundance. This population shows stronger year classes in warm years and poor year classes in cold, and warming has led to a northern range expansion in Norway and Greenland (Drinkwater 2006, 2009). As a result of warming, yields are predicted to increase by approximately 20 per cent for the most important cod and herring *Clupea harengus* stocks in Iceland, and approximately 200 per cent in Greenland over the next 50 years (Arnason 2007). Climate-driven fish invasions into the Arctic are expected to exceed any other LME (Cheung *et al.* 2009).

Despite the generally positive effects of climate-warming predicted for Arctic fisheries (excepting the loss of the current marine ecosystem), how invading species interact in this newly habitable environment and what sorts of ecosystems develop remain major ecological unknowns. This uncertainty has been recognized by, for example, the North-Pacific Fisheries Management Council, which has closed extensive shelf areas to fishing in order to conduct baseline research and to protect critical crab habitat from the northward expansion of trawlers into newly ice-free waters (Stram & Evans 2009). This precautionary approach is an important first step towards achieving a viable fishery, but it remains to be determined whether new Arctic fisheries can be developed in a sustainable and equitable way.

Bering Sea fisheries provide 50 per cent of United States domestic seafood production and are the largest contributor to US seafood exports, with species such as Pacific halibut *Hippoglossus stenolepis*, various ground-fish and salmon, sablefish *Anoplopoma fimbria* and crab (NMFS 2008). One-third of the total US crab catches originate here, as do an annual 2 billion kg of pollock *Theragra chalcogramma* (Woodby *et al.* 2005), and these resources are important for the diets and livelihoods of rural and indigenous people in Alaska, Chukotka, Northern Canada and elsewhere. Participation in the Bering Sea's commercial and subsistence fisheries is vital for coastal livelihoods, and their management has been well regarded in terms of sustainability (Woodby *et al.* 2005).

Most fisheries in the Bering Sea are managed under a limited access privilege system that provides a substantial flexibility for fishers responding to weather and ocean conditions, though not equally among fishers (Loring *et al.* in press). Faced with the impacts of climatic change, some participants have more room to adapt than others (Ford 2009; Loring & Gerlach 2010). Often large commercial operations can afford to fish in inclement weather, absorb fuel price shocks and follow large-scale movements of stocks, while small-scale fishers are vulnerable to small increases in fuel price that can limit time on the water. With such high levels of exposure, the majority of rural subsistence hunters and fishers suffer from asset-limited adaptive capacity.

In the past, northern peoples have enjoyed high adaptive capacity and success responding to environmental variability through social organizations that share resources and spread risk among individuals and communities (Moran 1981; Ford 2009); through local ecological knowledge and expertise that informs hunting and fishing practices while minimizing risks (Kawagley 1995); and through high levels of mobility that allow switching among hunting, fishing and gardening activities between seasons and years (Berkes & Jolly 2001; Loring & Gerlach 2010). However, many of these adaptive capacity components have been reduced by severe changes in sea ice conditions (Berkes & Jolly 2001); restrictive hunting and fishing seasons; jurisdictional conflicts among state, federal and private lands; and single-species management rather than an ecosystem-based approach (Schumann & Macinko 2007; Loring *et al.* in press). This combination of environmental and regulatory factors has drastically increased the vulnerability of Native hunters and fishers in ways that have had limited impact on large-scale commercial interests.

Although options for Native fishers are currently declining, cultural and intellectual capacity for adaptation persists at a high level, presenting a rare opportunity for indigenous peoples to benefit from climate change, even after the irreplaceable loss of traditional livelihoods. Tools and livelihood strategies in the region are highly advanced for regional and climatic adaptation (Moran 1981) and these components of adaptive capacity can be directed towards development of sustainable Arctic fisheries. Developing such a fishery requires government involvement, whereby local small-scale fishers are given regulatory authority through resource co-management arrangements (Huntington 2000; Loring *et al.* in press), as the asset wealth and low vulnerability of large-scale commercial interests would dominate entry into new fisheries. There is a clear moral imperative for local and Native control, as the climate warming that will create open-water Arctic fisheries is also responsible for eliminating their traditional livelihoods.

5. CONCLUSIONS

The future of marine fisheries will develop from a complex interaction of oceanographic conditions, physiological tolerances and thermally induced distribution shifts that cannot be predicted accurately. Although outcomes span a range of positive and negative outcomes among latitudes, all jurisdictions require forethought and planning to avoid the most negative effects of climate change on their fisheries. As it is highly unlikely that substantive emission reductions will occur in the medium term, and given that changes in fisheries driven by long-term temperature trends are already being observed, fisheries managers must plan and act to adapt to climate change.

(a) *Adaptation strategies*

Successful adaptation to climate change will depend heavily on local social and environmental conditions, with some societies being more flexible because of economic and cultural factors (Cinner *et al.* 2009*b*). Although reducing negative impacts such as overfishing will help reduce effects on fisheries (Brander 2010), nations with low adaptive capacity may find it difficult to change course, and small-scale fishers readily fall into poverty traps that greatly limit their ability to adapt (Sherman *et al.* 2009). Although the effects of climate change will ultimately reveal if existing livelihoods and management systems are resilient (Badjeck *et al.* 2010), there are several strategies likely to help societies adapt to the ecosystem consequences of widespread change.

1. *Divert effort*: as many fish communities are expected to change composition or decline in biomass, or both, fishers and fisheries regulators must prepare to shift target species from traditional stocks to new or underutilized ones, and to aquaculture. Most fisheries are location-specific and operate at utilization levels that make them inflexible (McIlgorm *et al.* 2010); however, they must be made flexible if they are to continue to support local communities. People need the ability to adjust not just where and when, but what they harvest. In those relatively rare circumstances in which existing fisheries select only a proportion of the available resource, bet-hedging through modest development of alternative fisheries less likely to decline should be adopted. For instance, promoting a gradual shift from reef-associated to pelagic species by establishing near-reef fish aggregation devices may help many Pacific Island states sustain local protein demands and livelihoods when the productivity of their reef fisheries decline (Bell *et al.* 2009). Options must be weighed carefully, however, as short-term adaptations targeting new species must account for their ecological impacts and effects on existing resource-users.

2. *Protect key functional groups*: local action to protect key functional groups may increase resilience to climate change effects. The clearest example is on coral reefs, where a variety of fishes play key functional roles in maintaining coral dominance over macroalgae, and these species are more vulnerable to fishing than to climate-driven habitat loss (Graham *et al.* submitted). Changing gear use or banning gears with large impacts on key species has been suggested to help maintain ecological function (Cinner *et al.* 2009*a*). Herbivory plays a key functional role on reefs, and herbivores are protected in some jurisdictions, such as herbivore fishing bans in Herbivore Fisheries Management Areas of Hawaii, that can help determine the wider applicability of such a focused management approach.

3. *Invest*: the societies best able to adapt to climate change are likely to be well-informed, well-capitalized and able to shift to alternative fisheries or activities (Brander 2010). Fishers in poorly capitalized, developing nations are least likely to be able to divert effort towards new or under-used resources that could meet local resource demands (Allison *et al.* 2009). Judicious capital investment in landing sites, engines and boats, and alternative gears would serve to improve access to other resources, but risk subsidizing overfishing. Recovery from acute disturbances such as storms requires public or private investment in insurance schemes that allow fishers to quickly return to fishing (Badjeck *et al.* 2010) and transitioning from traditional to novel fisheries requires interim support. Local scientific capacity to understand ecosystem ecology and regulate fisheries requires national and international investment in field and computing resources, and in the human capital needed to conduct research.

4. *Monitoring and indicators*: deciding what, where and when to monitor are among the most important decisions in the development of any fisheries adaptation plan. To act, regulators must understand the current state of the ecosystem (Vilhjálmsson *et al.* 2005) and this understanding can only come through monitoring of indicators showing changes in state (King & McFarlane 2006) that can be related to unfavourable thresholds (Mumby *et al.* 2007) and show how close the system is to reaching them (Scheffer & Carpenter 2003). Often quite simple biological indicators such as population variance (Brooks *et al.* 2006) or current abundance as a fraction of unfished abundance (Worm *et al.* 2009) can provide useful information but many of these are underused (Brander 2010). Tailoring indicators to the system being fished requires careful, well-informed thought about what provides the greatest level of contrast near transitions between ecosystem states. Development of social indicators and reference points is also an important, but as yet undeveloped, aspect of adaptation. For instance, measuring fishers income and the levels at which they fall into and get out of poverty traps could prove critical in helping to maintain coastal livelihoods.

5. *Decoupling from fisheries*: although fisheries have often provided a refuge for impoverished peoples (Tietze *et al.* 2000), fisheries in some areas are expected to collapse in response to repeated acute disturbance and increasing temperature. Programmes to deal with the effects of such losses would ideally be in place before they occur. Societies that fail to prepare for the threat of fisheries collapse may experience severe food shortages while those that prepare to divert nutritional needs and livelihoods to land or freshwater-based sources will fare better. Unfortunately, some coastal tropical regions most likely to collapse also have the least capacity to undertake such preparations.

A key challenge for future fisheries management is to determine in which combination these adaptation options should be applied to suit particular fisheries. Climate change is an environmental problem that forces individual fisheries jurisdictions to deal with the local and regional effects of factors beyond their control. The challenge for managers is to spread risks and remain nimble enough to ensure that fisheries are efficient, sustainable and productive, even as they undergo unprecedented change.

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